

Remarks

This Preliminary Amendment cancels without prejudice original claims 1-10 in the underlying PCT Application No. PCT/EP2004/050455 and adds new claims 11-28. The new claims conform to U.S. Patent and Trademark Office rules and do not add new matter to the application.

In accordance with 37 C.F.R. § 1.125(b), the Substitute Specification (including the Abstract, but without the claims) contains no new matter. The amendments reflected in the Substitute Specification (including Abstract) are to conform the Specification and Abstract to U.S. Patent and Trademark Office rules or to correct informalities. As required by 37 C.F.R. § 1.121(b)(3)(ii) and § 1.125(c), a Marked Up Version Of The Substitute Specification comparing the Specification of record and the Substitute Specification also accompanies this Preliminary Amendment. Approval and entry of the Substitute Specification (including Abstract) are respectfully requested.

The underlying PCT Application No. PCT/EP2004/050455 includes an International Search Report, dated August 2, 2004. The Search Report includes a list of documents that were uncovered in the underlying PCT Application.

Applicants assert that the subject matter of the present application is new, non-obvious, and useful. Prompt consideration and allowance of the application are respectfully requested.

Respectfully Submitted,

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## DEVICE FOR OPERATING A GAS SENSOR

Field of the Invention

The present invention ~~is based on~~ relates to a device for operating a gas sensor ~~according to the species defined in~~  
5 ~~the independent claim.~~

Background Information

In the reference book "Otto-Motor - Management/Bosch", Vieweg Publishing House, 1<sup>st</sup> edition, 1998, pages 22-23, a broadband lambda sensor is described, having a sensor  
10 chamber which is connected to a gas compartment via a diffusion barrier. Situated in the sensor chamber is an inner pump electrode which, together with an outer pump electrode and an electrolyte that is situated between the pump electrodes and conducts oxygen ions, forms a pump cell.  
15 Using the pump cell, oxygen ions of the gas can be pumped through the electrolyte out of, or into, the sensor chamber.

In addition to the pump cell, a measuring cell is provided that is disposed between the inner pump electrode and a reference-gas electrode, an electrolyte conducting oxygen  
20 ions likewise being situated between the inner pump electrode and the reference-gas electrode. The measuring cell corresponds to a Nernst cell, in which the potential difference forming in the thermodynamic equilibrium between the inner pump electrode and the air reference electrode is  
25 proportional to the logarithm of the relationship of the partial pressure of the gas to be analyzed in the sensor chamber and the partial pressure of the gas to be analyzed in the air reference.

A circuit configuration realized in analog circuitry has the  
30 task of influencing the oxygen partial pressure in the sensor chamber in such a way that the Nernst potential remains constant at a predefined value. For this purpose, the circuit configuration alters an electrical pump current

which acts upon the outer pump electrode. The polarity and the amount of the pump current depend upon whether and by what amount the predefined Nernst potential is exceeded or not attained. The pump current obtained appears at a load resistor as voltage, which is a measure for the concentration of the gas to be analyzed.

The Published German Patent Application DE 36 25 071-A1 describes a method for operating a sensor having variable ionic conductivity, as well as a device for implementing the method, in which the sensor, in cyclically proceeding operations, is acted upon in pulse-like fashion by a current supplied from a constant current source. The resulting voltage at the sensor is a measure for the relative atmospheric humidity to which the sensor is exposed. The pulse-like feeding of the current prevents polarization effects at the electrodes of the sensor. The use of a constant current, which can have an alternating polarity, permits a simple evaluation of the sensor voltage resulting at the sensor element.

The An object of the present invention is to provide a device for operating a gas sensor, which contains a circuit configuration that is easy to implement and permits a precise, low-drift and low-offset measurement

~~This objective is achieved by the features set forth in the independent claim.~~

#### ~~Summary of the Invention~~Summary

According to the present invention, a constant current source is provided for supplying the pump current. According to a first ~~alternative~~example embodiment, the constant current source is adjustable to several specifiable current levels. According to a second ~~alternative~~example embodiment which, if desired, may be provided in addition to the first ~~alternative~~example embodiment, the constant current source

allows for a clocked operation with ON phases and OFF phases, the duration of the ON phases and/or the duration of the OFF phases being specifiable.

5 The device of the present invention may be realized to a great extent in digital circuitry. A comparatively precise recording of the pump current, and therefore of the measuring signal, is thereby possible. The errors due to drift and offset, which in analog circuitry can only be  
10 controlled with costly measures, are avoided to the greatest extent possible. Moreover, the recording of the pump current is independent of an electrical capacitance of the gas sensor.

15 According to the first alternative example embodiment, the device of the present invention allows the stipulation of different amounts of the constant currents. In a steady-state operating condition, in which the concentration of the gas to be measured does not change or changes only  
20 insignificantly within the measuring time interval considered, the constant current known in the circuit configuration is identical to the pump current. In the usually non-steady conditions, it is possible to obtain the pump current by a simple averaging over a temporally  
25 predefined measuring window. The averaging turns out to be particularly easy, since both the times in which the predefined constant current is flowing, and the amount of the constant current in the circuit configuration are known.

30 The second alternative example embodiment, which allows for a clocked operation with ON phases and OFF phases, permits the stipulation of an average pump current by varying the duration of the ON phases and/or OFF phases. The second alternative example embodiment permits a realization of the

constant current source in the extreme case with only one specifiable level.

The most flexible design approach allows for a combination of the first and second ~~alternatives~~ example embodiments. The combination makes it possible to flexibly predefine the amounts of the constant currents and the duration of the ON phases and/or OFF phases. Since the device of the present invention for operating the gas sensor includes a control loop, which exists because a change in the pump current influences the measuring voltage that on its part can lead again to an adjustment of the pump current, using the measures provided according to the invention, it is possible to optimize the control response in view of accuracy and speed of the control.

The device ~~of~~ according to the present invention may be directly addressed via standardized interfaces by further electrical control units which are not the subject matter of the present patent application. Only a small number of additional circuitry measures are necessary for this purpose. The signals occurring in the device of the present invention exist largely in digital form, so that the signal processing may take place to the greatest extent possible in a computer. This permits a miniaturization of the circuit configuration, while at the same time increasing the functionality and the possibility of altering the functionality of the device. Adaptation to different gas-sensor designs, or adaptation for the compensation of manufacturing tolerances of a gas-sensor series, is possible in a simple manner using software adaptations, without altering the hardware.

~~Advantageous further developments and refinements of the device according to the present invention for operating a gas sensor are yielded from the dependent claims.~~

According to one ~~refinement~~example embodiment, the constant current source permits the stipulation of constant currents that have both positive and negative polarity.

One example embodiment allows for averaging over a predefined measuring time. The averaging makes it possible to increase accuracy in recording the pump current, particularly in the case of non-steady operations in which control actions occur. By adapting the measuring time, which corresponds to a low-pass filter function, the time characteristic of the pump current may be smoothed at the same time.

The device ~~ef~~according to the present invention permits the ascertainment of the pump current by simple counting operations. Given a predefined current level and predefined duration of the ON phases and/or OFF phases, the count of the number of ON phases or OFF phases within the predefined measuring time represents a direct measure for the pump current. An automatic control of the measuring voltage is possible by a control of the constant current source as a function of a comparison between a predefined setpoint measuring voltage and the actual measuring voltage. The analog measuring voltage ~~is preferably~~may be converted to a digital signal in an analog-to-digital converter, so that it is possible to implement the device of the present invention to the greatest extent possible in digital circuitry.

One further ~~development~~example embodiment of the device according to the present invention provides for a gas sensor which includes a plurality of pump cells that, for example, are able to be exposed to different gases to be analyzed. Only one measuring cell is needed for the plurality of pump cells. By a time coordination, one and the same constant current source is able to act upon all pump cells with one pump current in temporal sequence. If the resulting times yield values which are too high for the current-free state of some pump cells, the constant current source and its control may be provided multiple times accordingly. The additional expenditure is thereby limited, since the

functions are able to be implemented repeatedly in a computer, e.g., a microprocessor, without great expenditure.

The device ~~of~~according to the present invention is particularly suitable for operating a gas sensor situated in the exhaust gas of an internal combustion engine. The far-reaching possibility of digitalization has important advantages in this use of the gas sensor with regard to the surroundings contaminated with electromagnetic disturbances.

~~Additional advantageous refinements and embodiments of the device according to the present invention for operating a gas sensor are yielded from further dependent claims and from the following description.~~

#### ~~Brief Description of the Drawing~~Brief Description of the Drawings

Fig. 1 shows a schematic cross-sectional view throughof a gas sensor~~7~~.

Fig. 2 shows a block diagram of an example embodiment of a device according to the present invention for operating the gas sensor shown in Figure 1~~7~~ and.

~~Fig~~Figs. 3a-3c show various signal patterns as a function of time, which occur in the configuration shown in Figure 2.

#### Detailed Description

Figure 1 shows a schematic cross-sectional view throughof a gas sensor 10 which includes a pump cell 13 situated between an outer pump electrode 11 and an inner pump electrode 12. Inner pump electrode 12 is situated in a sensor chamber 14 that receives the gas to be measured via a diffusion barrier

15. Also situated in sensor chamber 14 is an inner measuring electrode 16 which, together with an outer measuring electrode 18 disposed in a gas reference space 17, forms a measuring cell 19.

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Outer pump electrode 11, which is connected to a pump electrode connection APE, receives a pump current  $I_p$ . Inner pump electrode 12, which is electrically connected to inner measuring electrode 16, is connected to a sensor-chamber connection IPE. Outer measuring electrode 18 is connected to a measuring-signal connection LR.

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Figure 2 shows a block diagram of a device for operating gas sensor 10. The equivalent electrical, ~~equivalent~~ circuit diagram of gas sensor 10 has a pump-cell voltage  $U_{APE}$  and a pump-cell resistor  $R_{APE}$  between pump-electrode connection APE and measuring-signal connection LR. Gas sensor 10 further has a measuring voltage  $U_{IPEactual}$  and a measuring-cell resistor  $R_{IPE}$  between measuring-signal connection LR and sensor-chamber connection IPE. Sensor-chamber connection IPE is connected to a circuit ground 20.

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Measuring-signal connection LR, to which a sensor voltage  $U_{LR}$  is applied, is connected to a sample-and-hold circuit 21 that is connected in series to an analog-to-digital converter 22, which transmits a digitalized measuring voltage  $U_{IPEactuald}$  to a comparator 23. Comparator 23 compares digitalized measuring voltage  $U_{IPEactuald}$  to a setpoint voltage  $U_{IPEsetpoint}$  and emits a differential signal 24 to a decision logic 25. Decision logic 25 emits a first switching signal  $St1$  to a first switch S1, a second switching signal  $St2$  to a second switch S2, and a counting signal 26 to a counter 27.

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First switch S1 is connected to a positive voltage source  $U_+$ , and the second switch is connected to a negative voltage source  $U_-$ . First switch S1 is able to switch positive voltage source  $U_+$ , and second switch S2 is able to switch negative voltage source  $U_-$  to a current-source resistor  $R_i$ , that is connected to pump-electrode connection APE, into which pump current  $I_p$  flows. To control sample-and-hold circuit 21 and decision logic 25, a clock generator 28 is provided that supplies a clock signal TAKT.

Figures 3a-3c show various signal patterns as a function of time  $t$ , which occur in the device shown in Figure 2.

Figure 3a shows sensor voltage ULR as a function of time  $t$ . Sensor voltage ULR is obtained from the superimposition of the voltage of measuring-voltage source  $UIPE_{actual}$  and a fault voltage  $U_F$ , which is obtained due to the voltage drop at pump-cell resistor RAPE based on pump current  $I_p$ . Fault voltage  $U_F$  occurs during ON phases TD, i.e., while pump current  $I_p$  is flowing. During OFF phases TA, pump current  $I_p$  is interrupted, so that measuring voltage  $UIPE_{actual}$  is present as sensor voltage ULR.

Figure 3b shows pump current  $I_p$  as a function of time  $t$ . In a first time interval, which is between a first and a sixth instant  $T_1$ ,  $T_6$ , during ON phases TD, pump current  $I_p$  occurs with a first amount  $I_+$ . During OFF phases TA and during a time interval which begins after sixth instant  $T_6$  and ends at a measuring time  $T_M$ , pump current  $I_p$  during ON phases TD is established at a second amount  $I_-$ . With the occurrence of measuring time  $T_M$ , the amount of pump current  $I_p$  during ON phase TD changes again to first amount  $I_+$ .

Figure 3c shows clock signal TAKT as a function of time  $t$ . During ON phases TD, clock signal TAKT has an ON level, and

during OFF phases TA, an OFF level. Clock signal TAKT has a period duration TP. ON phase TD and OFF phase TA occur within period duration TP.

5 The device ~~of~~according to the present invention for operating gas sensor 10 shown schematically in Figure 1 is explained in greater detail ~~based on~~in connection with the signal patterns, shown in Figures 3a-3c, which occur in the configuration shown in Figure 2:

10 Gas sensor 10 is situated, for example, in the exhaust gas of an internal combustion engine. In this practical application, gas sensor 10 detects a concentration of a gaseous component contained in the exhaust gas. It may be  
15 the residual oxygen concentration, for instance, or the nitrogen oxide (NOx) concentration. Outer pump electrode 11 and diffusion barrier 15 are exposed to the gas to be analyzed. The gas concentration in sensor chamber 14 may be altered by a gaseous-ion transport using pump cell 13. The  
20 concentration may be changed by applying a voltage to pump-electrode connection APE of outer pump electrode 11. Pump current  $I_p$  results based on the voltage.

Gas sensor 10 also includes measuring cell 19 formed between  
25 inner and outer measuring electrodes 16, 18. The concentration of the gas to be analyzed in sensor chamber 14 may be measured by measuring cell 19 on the basis of a flow of gaseous ions occurring in measuring cell 19. The voltage of measuring cell 19 is measuring voltage  $U_{IPEactual}$ , known  
30 as Nernst voltage. A prerequisite for the formation of the Nernst voltage is a thermodynamic equilibrium between the gaseous components of the gas to be analyzed. The concentration measurement is carried out as against the gas concentration which occurs in gas reference space 17. It is  
35 a space filled, for example, with air.

On condition that the concentration of the gas to be measured in gas reference space 17 is higher than the concentration in sensor chamber 14, the equivalent circuit diagram of gas sensor 10 shown in Figure 2 is applicable. Under the assumption indicated, the potential appearing at measuring-signal connection LR lies below the potential appearing at pump-electrode connection APE, but above the potential appearing at sensor-chamber connection IPE. The potentials are determined by the voltage sources shown in the equivalent circuit diagram of gas sensor 10 shown in Fig. 2. The voltages of the voltage sources, therefore measuring voltage UIPEactual and the pump-cell voltage of UAPE, are determined by the differences in concentration at measuring cell 19 and pump cell 13, respectively, which can be influenced by pump current  $I_p$ .

The configuration shown in Figure 2 ~~preferably~~ has the task of adjusting measuring voltage UIPEactual to setpoint voltage UIPEsetpoint. In the case of a gas sensor 10 which is intended to detect the concentration of the residual oxygen in the exhaust gas of an internal combustion engine in thermodynamic equilibrium, setpoint voltage UIPEsetpoint is set to a value, for example, which lies in the range of the air ratio  $\lambda$  of at least approximatively = 1, at which the oxygen concentration or the oxygen partial pressure changes by several powers of ten. Measuring voltage UIPEactual changes sharply accordingly. Setpoint voltage UIPEsetpoint is set, e.g., to a value of 450 mV.

Sensor voltage ULR shown in Figure 3a, ~~able to be~~ which is tapped off at measuring-signal connection LR, is ~~preferably~~ measured during OFF phases TA. The falsification of the voltage by fault voltage UF on the basis of pump current  $I_p$  at measuring-cell resistor RIPE is not applicable during OFF

phases TA of pump current  $I_p$ . Sensor voltage ULR is sampled by sample-and-hold circuit 21, controlled by clock signal TAKT, which is connected in series to and in front of analog-to-digital converter 22. Alternatively, sample-and-hold circuit 21 and analog-to-digital converter 22 may be interchanged in the configuration, so that an analog-to-digital conversion of measuring voltage UIPEactual may be provided immediately.

Digitalized measuring voltage UIPEactuald is compared to setpoint voltage UIPEsetpoint in comparator 23. Differential signal 24 is output to decision logic 25 as a function of the difference. Decision logic 25 activates either first switch S1 or second switch S2 using first switching signal St1 or second switching signal St2. The closing of first switch S1, which is connected to positive voltage source  $U_+$ , leads, in conjunction with current-source resistor  $R_i$ , to a pump current  $I_p$  having predefined magnitude  $I_+$ , shown in Figure 3b, which occurs within a time interval that lies between first instant T1 and sixth instant T6. First control signal St1, and therefore the occurrence of pump current  $I_p$  having first amount  $I_+$ , occurs during ON phases TD. In the exemplary embodiment shown, five ON phases TD are provided between first and sixth instants T1, T6.

In the exemplary embodiment shown, the configuration having positive or negative voltage source  $U_+$ ,  $U_-$  and current-source resistor  $R_i$ , is intended to form a switchable constant current source. Instead of the example embodiments shown, the constant current source may also be implemented with a greater degree of complexity, with the aim of being able to specify the pump current more precisely. On condition that current-source resistor  $R_i$  is of considerably higher resistance than the internal resistance of positive or negative voltage source  $U_+$ ,  $U_-$  and greater than pump-cell

resistor  $R_i$ , pump current  $I_p$  is determined essentially by the voltage of positive or negative voltage source  $U_+$ ,  $U_-$  and current-source resistor  $R_i$ . If only one predefined amount of pump current  $I_p$  is provided, the constant current source may be set to current levels  $I_+$ ,  $I_-$  shown in Figure 3b. By changing the voltage of positive and negative voltage sources  $U_+$ ,  $U_-$  and/or the resistance value of current-source resistor  $R_i$ , it is possible to predefine different current levels.

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Upon closure of second switch  $S_2$ , which is connected to negative voltage source  $U_-$ , in conjunction with current-source resistor  $R_i$ , the second amount  $I_-$  of pump current  $I_p$  results. This situation is shown between the sixth instant and measuring time  $T_M$  in Figure 3b. For example, the four ON durations  $T_D$  shown occur within the time interval. In the exemplary embodiment shown, it is assumed that at sixth instant  $T_6$ , differential signal 24 signals that digitalized measuring voltage  $U_{IPEactuald}$  has exceeded setpoint voltage  $U_{IPEsetpoint}$ , so that in period duration  $T_P$  following instant  $T_6$ , first switching signal  $St_1$  is withdrawn and second switching signal  $St_2$  is output during ON phases  $T_D$  for closing second switch  $S_2$ . With the occurrence of measuring time  $T_M$ , differential signal 24 changes again. With the occurrence of measuring time  $T_M$ , one control oscillation is ended. A different embodiment of the automatic controller may lead to a different behavior.

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Because of the largely digital implementation of circuit components, pump current  $I_p$  may be easily ascertained. First and second amounts  $I_+$ ,  $I_-$  of the current of the constant current source are established by the voltage of positive and negative voltage sources  $U_+$ ,  $U_-$ , and by the amount of current-source resistance  $R_i$ . Pump current  $I_p$  may be ascertained by a simple counting operation of ON phases  $T_D$

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shown in Figure 3b, provided first and second amounts  $I_+$ ,  $I_-$  of pump current  $I_p$  are of equal value. The counting is accomplished by a count of ON durations  $TD$  occurring between first and sixth instants  $T_1$ ,  $T_6$ , and a count of ON durations  $TD$  occurring between sixth instant  $T_6$  and measuring time  $T_M$ . The difference is subsequently formed.

In the exemplary embodiment shown, measuring time  $T_M$ , over which the sum operation is carried out, is coincidentally exactly equated to one control oscillation. Measuring time  $T_M$  may be specified independently of the control oscillation. Measuring time  $T_M$  indicates the integration time for the averaging. The result of the averaging yields average pump current  $I_p$  acting upon outer pump electrode 11. Pump current  $I_p$  is a direct measure for the concentration of the gas to be analyzed, since the automatic control of pump current  $I_p$  is regulated as a function of constantly retained measuring voltage  $U_{IPEactual}$ . The averaging may be carried out in sliding fashion. Sliding averaging means that, for example, the current pulses are summed at each instant  $T_1 - T_9$ , up to the uniformly progressing measuring time  $T_M$ .

The resolution in ascertaining average pump current  $I_p$  is influenced by the determination of measuring time  $T_M$ . For example, if period duration  $TP$  is set to 0.1 ms and measuring time  $T_M$  is set to 10 ms, then the resolution amounts to  $T_M/TP = 100$ . Average pump current  $I_p$  may therefore be resolved in 1/100 steps of maximum possible average pump current  $I_p$ . In this context, the maximum possible average value of pump current  $I_p$  may amount to  $100 * U_+ * TD/R_i$  or  $100 * U_- * TD/R_i$ .

By stepping (or graduation) of ON durations  $TD$  and/or of first and/or second amount  $I_+$ ,  $I_-$ , it is possible to

optimize the control response with regard to accuracy and speed, and especially stability of the control.

A further ~~development~~example embodiment may provide that constant current source  $U+$ ,  $S1$ ,  $U-$ ,  $S2$ ,  $Ri$  is designed to be multi-step, in particular multi-step for both polarities, as well. If differential signal 24 indicates a larger difference between measuring voltage  $UIPE_{actual}$  and setpoint voltage  $UIPE_{setpoint}$ , a higher current amount may be specified for one or more ON times  $TD$  than in the case of a smaller difference.

In another ~~further development~~example embodiment, ON phases  $TD$  and/or period duration  $TP$  are variably specified. In this case, in response to a higher difference between measuring voltage  $UIPE_{actual}$  and setpoint voltage  $UIPE_{setpoint}$ , initially a longer ON phase  $TD$  may be specified for one or more period durations  $TP$  than if the difference were smaller.

One example embodiment provides for a combination of the further developments, so that with a change in the amounts  $I+$ ,  $I-$  of pump current  $I_p$ , as well as a change in ON phases  $TD$  and/or period durations  $TP$ , the quantity of electricity supplied to pump electrode 11 may be variably predefined according to the product  $I_p * TD$  in one period duration  $TP$ .

In the case of the further ~~development~~example embodiment, the change in pump current  $I_p$  to the other amounts  $I+$ ,  $I-$ , as well as the change in the duration of ON phases  $TD$  are to be taken into consideration in the counting of ON phases  $TD$  in counter 27.

In another further ~~development~~example embodiment, instead of the one pump cell 13, gas sensor 10 has further pump cells.

The individual pump cells may receive pump current  $I_p$  from constant current source  $U_+$ ,  $S1$ ,  $U_-$ ,  $S2$ ,  $R_i$  in temporal sequence. However, a plurality of constant current sources may also be provided corresponding to the number of pump  
5 ~~current sources~~cell 13. To avoid a voltage drop in gas sensor 10 while sample-and-hold circuit 21 is sampling measuring voltage  $U_{IPEactual}$ , care must be taken that OFF phases TA exist simultaneously for all pump cells.

A device ~~is provided~~ for operating a gas sensor ~~(10)~~ that ~~includes~~having both at least one pump cell ~~(13)~~ and a  
5 measuring cell ~~(19)~~is provided. A constant current source  
~~(U<sub>+</sub>, S<sub>1</sub>, U<sub>-</sub>, S<sub>2</sub>, R<sub>i</sub>)~~ is provided that makes available a pump  
current ~~(I<sub>p</sub>)~~ which acts upon an outer electrode ~~(11)~~ of the  
pump cell ~~(13)~~. The constant current source ~~(U<sub>+</sub>, S<sub>1</sub>, U<sub>-</sub>, S<sub>2</sub>, R<sub>i</sub>)~~  
10 provides at least two different amounts ~~(I<sub>+</sub>, I<sub>-</sub>)~~ of the  
pump current ~~(I<sub>p</sub>)~~ and/or allows for an alternating operation  
having ON phases ~~(T<sub>D</sub>)~~ and OFF phases ~~(T<sub>A</sub>)~~, the duration of  
the ON phases ~~(T<sub>D</sub>)~~/OFF phases ~~(T<sub>A</sub>)~~ being specifiable. The  
device ~~can~~may be largely implemented in digital circuitry  
and adapted to different requirements.

15  
~~(Fig. 2)~~